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TECHNICAL REPORT

AMRA TR 63-35

EFFECT OF TEMPERING ON NOTCH PROPERTIES OF D6AC ALLOY STEEL SHEET

by

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DECEMBER 1963

The findings in this report are not to be construed as an official Department of the Army position.

Rocket motor materials

Notch testing - sheet materials

Steel, high strength

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EFFECT OF TEMPERING ON NOTCH PROPERTIES OF D6AC ALLOY STEEL SHEET

ABSTRACT

A study of the strength and notch properties of D6AC (consumable electrode, vacuum-melted Cr-Mo-V) steel sheet, 0.040 inch thick, was conducted to evaluate the effect of tempering for various test temperatures. Smooth tensile, edge-notched tensile, and precracked subsize Charpy specimens were employed. Tempering in the range of 1000 F to 1100 F provided good fracture toughness with slight loss in strength properties that would be expected at higher tempers. The results are compared with burst tests conducted on Shillelagh motor cases made from the 0.040-inch-thick D6AC steel.

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INTRODUCTION

During October 1961, at the request of the U. S. Army Missile Command, the U. S. Army Materials Research Agency (AMRA) conducted a series of burst tests to evaluate the adequacy of the H11 steel being used in the Shillelagh missile rocket motor cases. When brittle fractures were observed in cases which were burst at -65 F, AMRA recommended a change from H11 steel to D6AC steel for this application. The recommendation was accepted and AMRA was asked to conduct burst tests on the D6AC Shillelagh rocket motor cases when they became available. While the missile case was being redesigned and fabrication procedures were being established by the prime contractor, the smooth and notch tensile properties of 0.040-inch-thick D6AC alloy sheet were studied in order to have supplementary data available for subsequent evaluation of the adequacy of the D6AC alloy for the rocket motor case application.

MATERIAL

The material used in this investigation was consumable electrode vacuum-melted D6AC steel. It was received in the hot-rolled and annealed condition and was 0.060-inch thick. The supplier's chemical analysis and that obtained by AMRA are shown in Table I.

TABLE I

CHEMICAL COMPOSITION

	Element (weight percent)								
Analysis	C	Mn	P	S	Si	Ni	Cr	Mo	V
Composition Limits	0.42-0.48	0.60-0.90	0.015 max.	0.015 max.	0.15-0.30	0.40-0.70	0.90-1.20	0.90-1.10	0.05-0.10
Manufacturer	0.44	0.77	0.009	0.009	0.24	0.52	1.08	1.06	0.09
AMRA	0.49	0.84	0.008	0.008	0.26	0.58	1.10	1.07	0.08

All material was subjected to a 20-minute normalization at 1650 F followed by air cooling. After normalizing, the material was austenitized at 1650 F for 20 minutes and air cooled. This treatment rendered the material fully martensitic. The austenitizing temperature of 1650 F was chosen to eliminate the possibility of free ferrite being present as has occurred at lower austenitizing temperatures.[1] After cooling, samples A through F were double tempered and sample G was triple tempered as indicated in Table II.

TABLE II

TEMPERING TEMPERATURE OF D6AC STEEL

Specimen Series	Temper (°F)	Time
A	800	1 + 1 hr AC
B	900	"
C	950	"
D	1000	"
E	1050	"
F	1100	"
G	400 then 600	1 hr AC 2 + 2 hr AC

The maximum observed decarburization was 0.0065 inch, which was later eliminated during Blanchard grinding to the 0.040-inch thickness.

EXPERIMENTAL PROCEDURE

All blanks were cut from the sheet in the transverse direction. After heat treatment, blanks were surface ground down to final thickness and finish machined. For each condition of heat treatment, 10 AMRA standard sheet tensile specimens and 10 AMRA standard flat tensile edge-notched specimens were prepared (for dimensions see Figure 1). These specimens were then tested at five test temperatures, encompassing the range of +70 F to -200 F. After testing the notched tensile specimens, two sheet Charpy specimens were taken from the shoulder of one of the broken halves. The Charpy specimens were cut so the crack would propagate in the same direction as in the notched tensile specimens. The Charpy specimens were precracked by fatiguing and were tested on a 16 ft-lb capacity machine at the same temperature as the tensile specimen from which they were cut.

The values of the fracture toughness, K_c, were based on percent shear measurements and are thus K_{c4} values in the standard ASTM designation.[2] G_c values calculated from these K_{c4} measurements were correlated with W/A values (energy per unit area values measured in in-lb/sq in.) obtained from the precracked Charpy specimens.

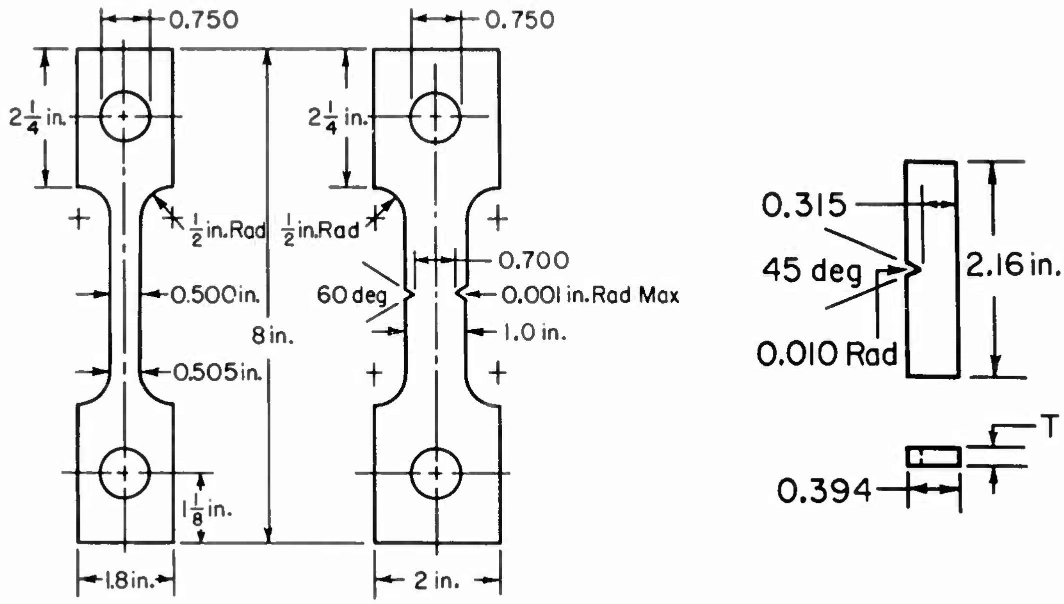
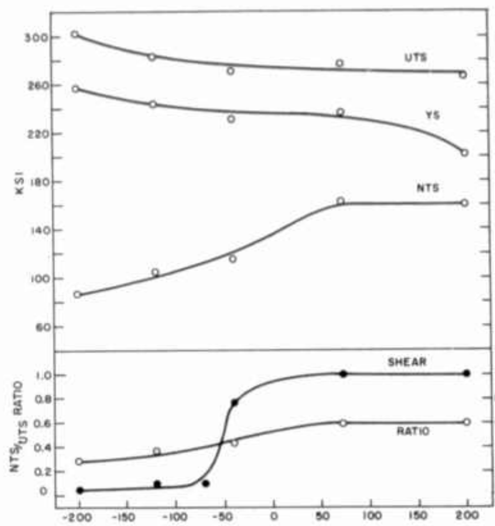


Figure 1. SHEET SPECIMEN DIMENSIONS

RESULTS AND DISCUSSION

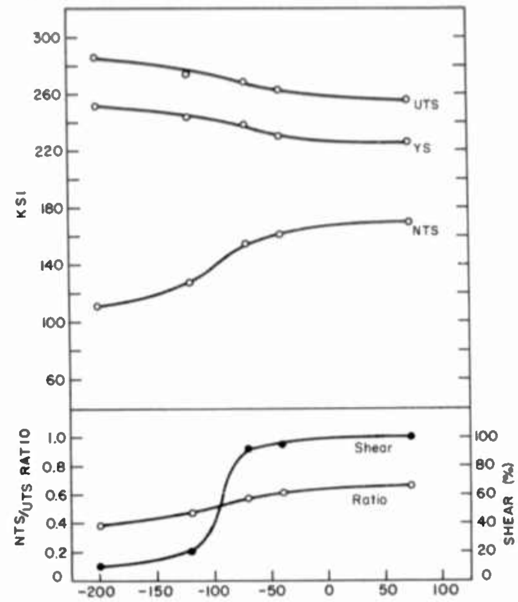
The smooth and notch tensile properties for each tempering temperature are plotted versus test temperatures in Figures 2 through 8; the transition properties are shown in Figure 9; and the fracture toughness data versus tempering temperature are presented in Figures 10 and 11. The data from which these figures were prepared are tabulated in the Appendix.

The tempering response of the smooth and notch tensile properties of D6AC sheet presented in Figures 2 through 8 are as one would have predicted. Increasing the tempering temperature decreases both ultimate and yield strengths. The ultimate strength at room temperature falls from about 275 ksi for 600 F tempers to 232 ksi for the 1100 F temper. The yield strength at room temperature falls from about 235 ksi to about 210 ksi over this same tempering range. The notch properties also follow a rather predictable pattern. As the tempering temperature increases, the notch strength increases, and the deterioration of notch strength with falling test temperatures becomes less pronounced. This is demonstrated in the plots of notch strength and notch/unnotch ratio in Figures 2 through 8.



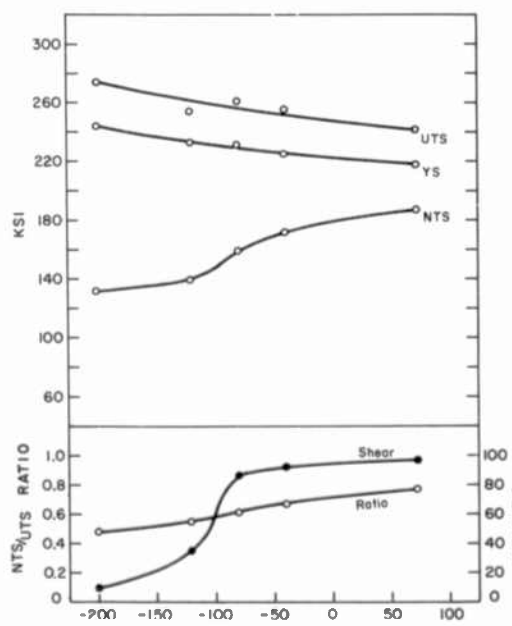
Test Temperature (F)

Figure 2. 600 F Temper



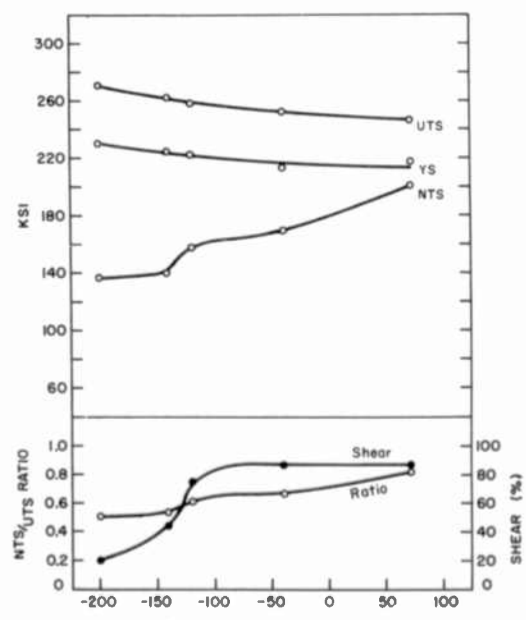
Test Temperature (F)

Figure 3. 800 F Temper



Test Temperature (F)

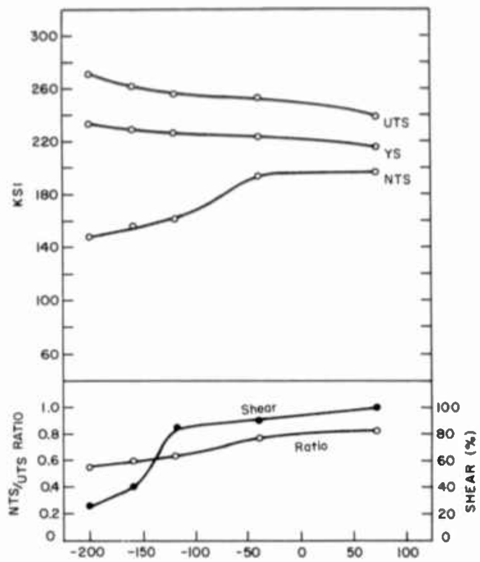
Figure 4. 900 F Temper



Test Temperature (F)

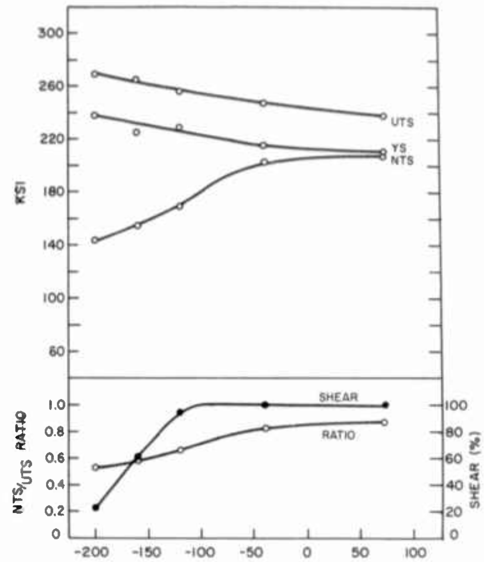
Figure 5. 950 F Temper

TENSILE PROPERTIES OF D6AC AS A FUNCTION OF TEST TEMPERATURE



Test Temperature (F)

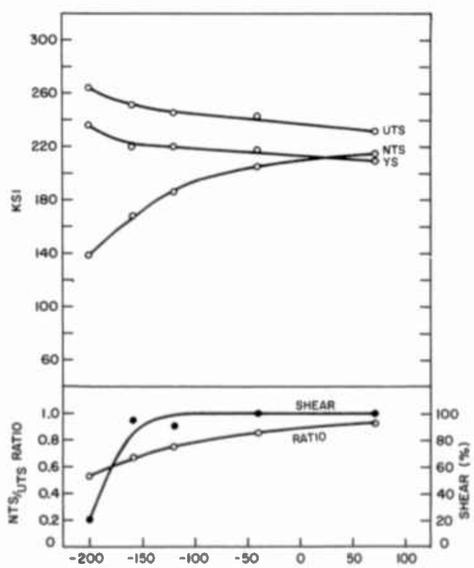
Figure 6. 1000 F Temper



Test Temperature (F)

Figure 7. 1050 F Temper

TENSILE PROPERTIES OF D6AC AS A FUNCTION OF TEST TEMPERATURE

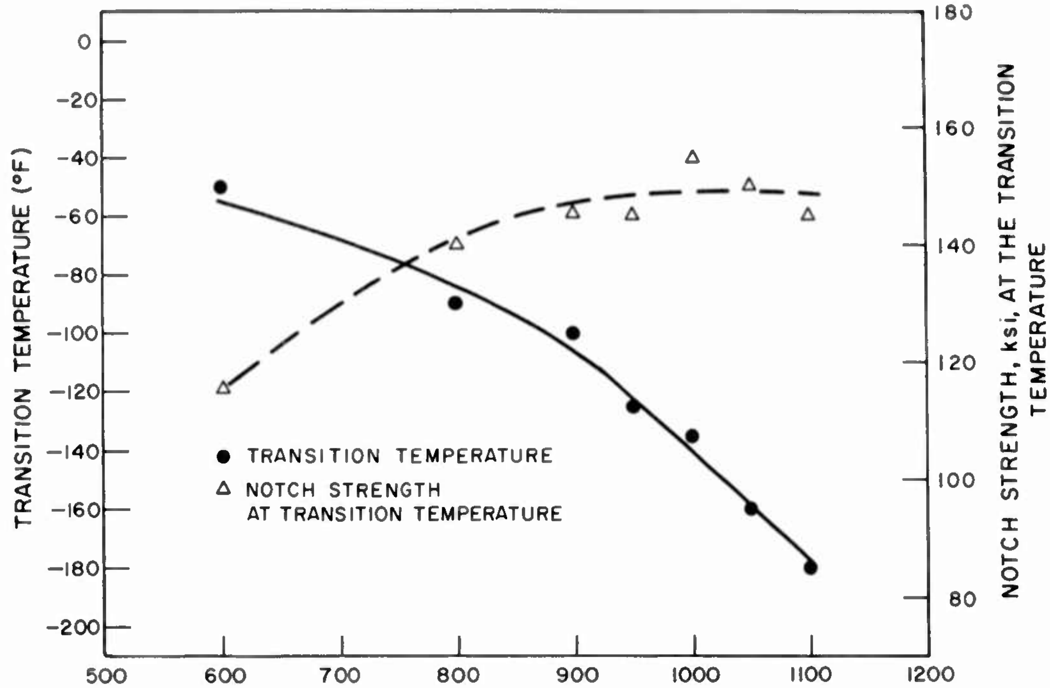


Test Temperature (F)

Figure 8. 1100 F Temper

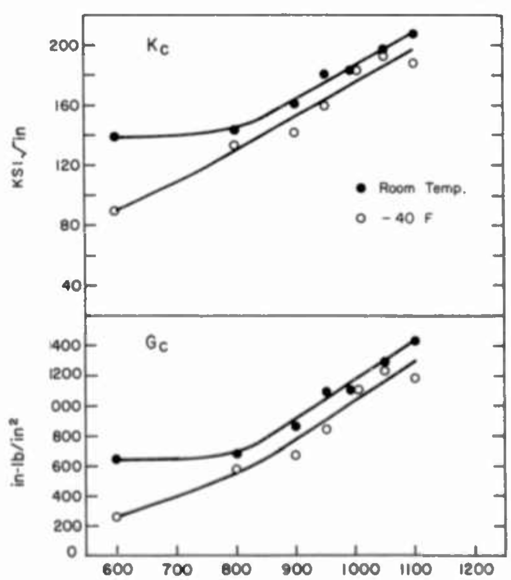
TENSILE PROPERTIES OF D6AC AS A FUNCTION OF TEST TEMPERATURE

The 50% shear lip transition temperatures, measured on edge-notched specimens, also undergo decreases as tempering temperature increases, as shown in Figure 9. When working with a notch-sensitive material, the notch strength becomes a more valid criteria of expected materials performance than the more traditional criteria of tensile or yield strength, especially when the materials may be used at a temperature below its shear transition temperature. This criteria is particularly important in a material such as the one studied in this report where, in all but one instance, the notch strength is significantly below the yield strength. For this reason, the notch strength at the shear transition temperature versus tempering temperature is also plotted in Figure 9, making it possible to obtain both the 50% shear transition temperature and the notch strength at this temperature for 0.040-inch D6AC sheet material as a function of tempering temperatures.



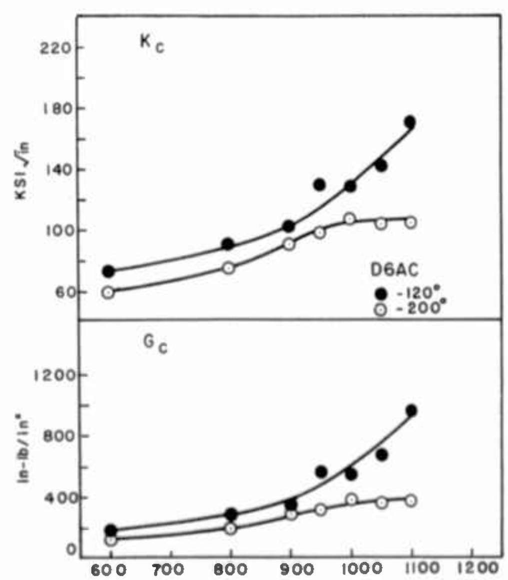
Tempering Temperature (F)

Figure 9. PERCENT SHEAR TRANSITION TEMPERATURE AND NOTCH STRENGTH AT THE TRANSITION TEMPERATURE OF D6AC AS A FUNCTION OF TEMPERING TEMPERATURE



Temper (F)

Figure 10. FRACTURE TOUGHNESS OF D6AC AT ROOM TEMPERATURE AND -40 F AS A FUNCTION OF TEMPERING TEMPERATURE



Temper (F)

Figure 11. FRACTURE TOUGHNESS OF D6AC AT -120 F AND -200 F AS A FUNCTION OF TEMPERING TEMPERATURE

The fracture toughness of D6AC 0.040-inch sheet measured by K_c and G_c values as a function of tempering temperature for tests at room temperature and -40 F is shown in Figure 10. It is observed that for tempers above 800 F there is little difference in fracture toughness at a given temper between the two test temperatures. In Figure 11, however, a large falloff in fracture toughness is observed as testing temperature is decreased to -120 F and -200 F. Only the 1100 F temper exhibits adequate fracture toughness at -120 F, based on the criteria of a minimum G_c of 1000 in-lb/sq in. From the figures and the data it is obvious that for both high strength and toughness at the widest variety of test temperatures, the optimum tempering range is 1000 F to 1100 F. It is especially interesting to note that in this range the designer is provided a material with a yield strength of about 216 ksi and a G_c of over 1000 in-lb/sq in. for use at temperatures down to -40 F, or a yield strength of about 210 ksi and fracture toughness values of 1000 in-lb/sq in. at temperatures in the vicinity of -100 F. The rapid falloff in fracture toughness when tempering below 1000 F and the relatively poor low temperature properties obtained at these tempers should preclude the use of such materials when notch sensitivity is a consideration or when low temperature service is a probability.

It was observed that the notched tensile specimens exhibited four distinct types of fracture surfaces when broken. These are shown in Figure 12. If one of the specimens in a given test broke in mode 1 or 2 and one broke in mode 3 or 4, an attempt was made to see if a significant difference in the notch tensile strengths occurred. It was found that such differences that did occur were often less than the differences in the scatter obtained when both bars would break in the same mode (e.g., without the 180-degree rotation of the shear lip). Although the observation from this study is that the different fracture appearances with the same percent shear lip do not affect the notch strength*

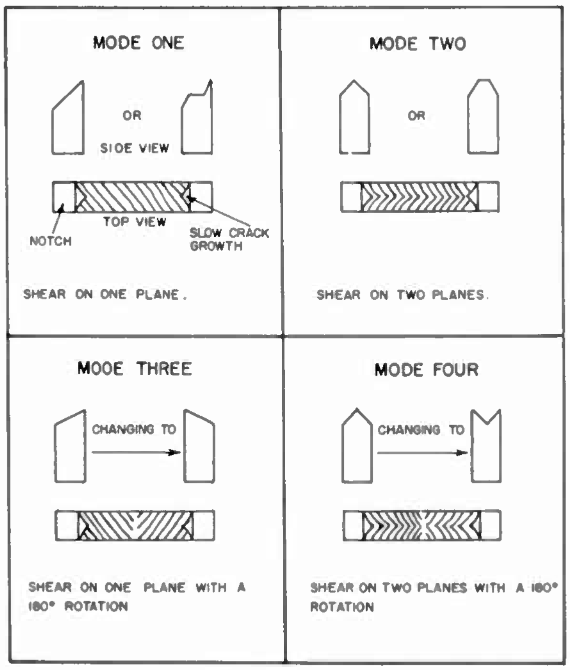


Figure 12. OBSERVED MODES OF CRACK PROPAGATION

*It must be remembered that a correlation does exist between percent shear and fracture toughness and that the values of K_c were calculated using a factor which is dependent on the percent shear (see Reference 2).

(and hence K_c), there were not enough specimens to test for each specific condition to give statistical validity to this observation. It is hoped, therefore, that in future studies of this nature investigators will note the fracture mode as well as the tensile and notch properties so that enough data for a valid statistical analysis may be accumulated.

Other investigators[3] have shown that values of energy per unit area (W/A values) obtained from precracked sheet Charpy specimens can be correlated with the critical strain energy release rates (G_c) as calculated from notched sheet specimens. However, their study showed somewhat more scatter than desirable in order to have confidence in using precracked sheet Charpy specimens as a substitute for the more expensive (in both time and money) edge- or center-notched sheet tensile tests for determining fracture toughness. It was felt that taking sheet Charpy specimens from the same notched tensile specimens that were used to obtain the fracture toughness data would considerably reduce the scatter in the G_c versus W/A correlation. As can be seen from Figure 13, the scatter is equal to that in Reference 3 and is considerable. This is surprising since several different high strength steels were used in their correlation, while this study used only one. However, if the average rather than the individual values of the two Charpy specimens cut from each notched specimen is plotted, the scatter is reduced considerably (see Figure 14). Since averaging two sheet Charpy specimens reduces the scatter, further reductions in scatter might be anticipated if three or more specimens are used.

As part of another program currently being conducted by this Laboratory, Shillelagh rocket motor cases* were tested under varying conditions of testing temperature and pre-existent crack length. These motor cases were austenitized at 1650 F, quenched into salt at 400 F, and tempered at 1025 F. They had a wall thickness of 0.047 inch as compared to the 0.040-inch thickness of the sheet material tested. All the cases broke in full shear at temperatures down to -85 F. The K_c values calculated on the basis of the Boeing[4] cylindrical pressure vessel formula for through-the-thickness cracks were consistently 10 to 20% below those obtained from the sheet material. This difference may be attributed to variations in thickness, processing history, and heat treatment. It is also interesting to note that all cases tested without pre-existent cracks burst near their ultimate strengths and that no premature failures occurred.

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*"Burst Tests of D6AC Shillelagh Missile Motor Cases," unpublished research at AMRA by R.N. Katz

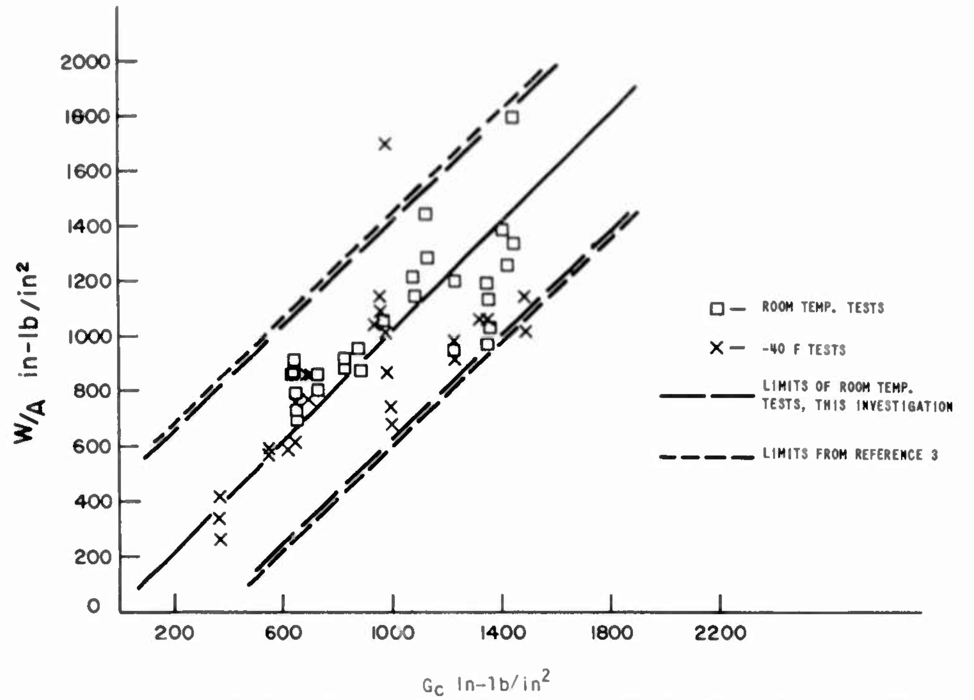

Figure 13. FRACTURE TOUGHNESS VALUES OBTAINED FROM EDGE-NOTCHED TENSILE SPECIMENS VERSUS W/A VALUES OBTAINED FROM PRECRACKED CHARPY SPECIMENS, USING INDIVIDUAL CHARPY VALUES.

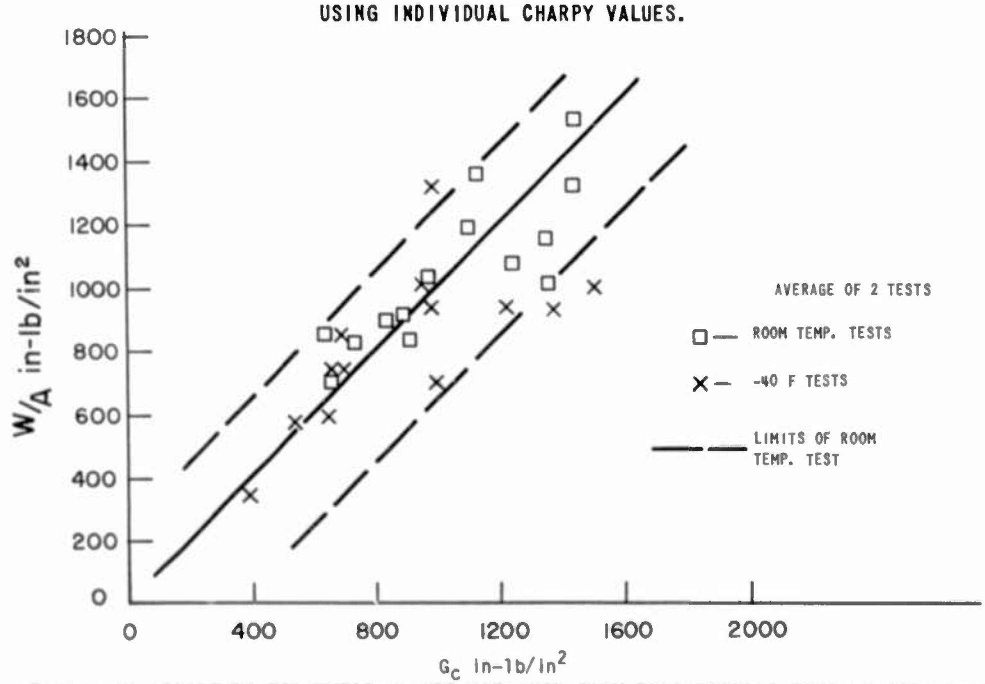

Figure 14. FRACTURE TOUGHNESS VALUES OBTAINED FROM EDGE-NOTCHED TENSILE SPECIMENS VERSUS W/A VALUES OBTAINED FROM PRECRACKED CHARPY SPECIMENS, USING THE AVERAGE OF TWO CHARPY VALUES.

CONCLUSIONS

1. The best combination of notch and tensile properties in 0.040-inch-thick D6AC sheet are obtained by tempering between 1000 F and 1100 F, within the range of tempers studied.

2. The precracked sheet Charpy specimen provides better correlation with G_c values than previously observed, if several specimens in the same condition of heat treatment, chemistry, and test variables are averaged.

FUTURE WORK

A continuation of the study on the sheet tensile and notch properties is underway. It will entail a determination of the critical thickness of D6AC sheet for various heat treatments and testing temperatures. A fuller investigation into the reliability of the precracked sheet Charpy specimen as a means of obtaining fracture toughness and critical thickness data will be undertaken.

APPENDIX

Tensile and Notch Properties of 0.040-inch D6AC Sheet

Test Temperature (F)	Yield Strength (ksi)	Tensile Strength (ksi)	NTS (ksi)	NTS/UTS	Shear (%)	K_{c4} (ksi$\sqrt{\text{in.}}$)	G_c $\left(\frac{\text{in-lb}}{\text{sq in.}}\right)$
600 F Temper							
+200	202.5	266.5	160.0	0.60	100	137.0	625
RT	236.0	276.5	163.5	0.59	100	139.0	645
-40	231.5	270.5	115.0	0.43	78	90.0	270
-70	236.5	280.5	168.0	0.60	10	118.5	470
-120	244.0	283.5	105.5	0.37	10	71.5	170
-200	257.5	302.5	86.5	0.29	5	57.5	110
800 F Temper							
RT	226.5	256.0	170.0	0.66	100	143.0	680
-40	231.0	263.0	161.0	0.61	95	133.0	590
-70	238.5	269.5	154.0	0.57	93	126.5	535
-120	244.5	274.0	128.0	0.47	20	89.5	265
-200	251.5	287.0	110.0	0.38	10	74.5	185
900 F Temper							
RT	218.5	242.0	187.0	0.77	98	160.5	860
-40	225.5	255.5	172.0	0.67	93	142.0	670
-80	231.5	261.5	159.0	0.61	90	128.5	550
-180	232.0	254.0	139.0	0.55	35	101.5	345
-200	244.0	274.0	131.5	0.48	10	98.0	275
950 F Temper							
RT	219.0	247.0	201.0	0.82	88	181.5	1090
-40	213.5	252.0	169.5	0.67	88	158.5	840
-120	222.5	258.0	158.0	0.61	65	129.0	550
-140	225.5	263.0	139.5	0.53	45	104.0	360
-200	230.0	271.0	137.0	0.51	20	97.0	315
1000 F Temper							
RT	216.5	238.5	197.0	0.83	100	182.5	1110
-40	223.5	253.5	193.5	0.77	90	182.5	1110
-120	226.5	256.0	161.0	0.63	85	128.0	545
-160	229.0	262.5	156.0	0.60	40	114.0	435
-200	233.5	271.5	147.5	0.55	25	106.5	380
1050 F Temper							
RT	211.5	237.5	207.0	0.87	100	197.0	1295
-40	215.0	247.5	203.5	0.82	100	192.5	1235
-120	229.0	256.0	169.0	0.66	95	141.0	665
-160	224.5	265.0	154.0	0.58	63	115.5	445
-200	237.5	269.0	143.5	0.53	23	103.0	355
1100 F Temper							
RT	209.5	232.0	215.5	0.93	100	207.5	1435
-40	218.5	243.0	205.2	0.85	100	188.0	1180
-120	219.5	244.5	185.5	0.75	90	169.5	960
-160	220.0	251.0	168.0	0.67	95	143.5	685
-200	236.5	264.0	138.5	0.53	20	104.0	360

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Technical Report AMRA TR 63-35, December 1963, 14 pp - illus - tables, AMCMS Code 5025.11.843, D/A Project 1A024401A111, Unclassified Report

A study of the strength and notch properties of D6AC (consumable electrode, vacuum-melted Cr-Mo-V) steel sheet, 0.040 inch thick, was conducted to evaluate the effect of tempering for various test temperatures. Smooth tensile, edge-notched tensile, and precracked subsize Charpy specimens were employed. Tempering in the range of 1000 F to 1100 F provided good fracture toughness with slight loss in strength properties that would be expected at higher tempers. The results are compared with burst tests conducted on Shillelagh motor cases made from the 0.040-inch-thick D6AC steel.

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